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FUEL CELL SYSTEM CONTROL

Technical Field

[0001] The present invention relates generally to a fuel cell system for power generation and more particularly to a method for controlling fuel cell outputs to be compatible with an energy storage device.

Background Of The Invention

[0002] Fuel cell systems offer many advantages over conventional sources. In a fuel cell, electricity is generated electromechanically through the reaction of hydrogen with oxygen. The only reaction emission involved is water vapor, which is essentially harmless to the environment. This is in contrast to a conventional power generation system, which releases harmful emissions such as hydrocarbons, carbon monoxide and other chemicals.

[0003] Fuel cell systems that are used for power generation must be controlled to meet electrical demand under normal, as well as transient, operating conditions. Long term fluctuations in the external load must be taken care of within the fuel cell system through the system controls that lead to fuel and oxidant energy input and output.

[0004] The fuel cell power generation systems are typically complex in that they require a power conversion stage for interfacing the fuel cell and energy storage. The power conversion stage modifies the output voltage of the fuel cell to be compatible with the load or with additional power conversion

stages such as an inverter. Efficiency losses are incurred and additional cost added for each power conversion stage. Therefore, these power generation systems tend to be very costly.

Summary Of The Invention

[0005] It is an object of the present invention to provide a process for controlling a fuel cell system. It is another object of the present invention to reduce the overall cost of a fuel cell power generation system by eliminating the need for multiple power conversion stages. It is a further object of the present invention to manipulate fuel cell system variables in response to the total power load on the fuel cell in combination with an energy storage device.

[0006] In carrying out the above objects and other objects and features of the present invention, a control system and a method for separately controlling variables such as the mass flow, pressure, temperature, humidification, and utilization of air and fuel, to adjust the voltage of a fuel cell stack. According to the present invention, the fuel cell is directly paralleled to the energy storage device without the need for a power conversion stage. The fuel cell voltage is controlled in such a manner that it is made compatible with voltage characteristics of the energy storage device as a function of load current and the state of charge of the storage device.

[0007] The present invention may be useful in low cost, hybrid battery systems, where a fuel cell is partnered with an energy storage device. In such devices, the fuel cell provides long term power and the

energy storage device provides peaks of power and/or the ability to store power regenerated from the load.

[0008] Other objects and advantages of the present invention will become apparent upon reading the following detailed description and appended claims, and upon reference to the accompanying drawings.

Brief Description Of The Drawings

[0009] For a more complete understanding of this invention, reference should now be had to the embodiments illustrated in greater detail in the accompanying drawings and described below by way of examples of the invention. In the drawings:

[0010] FIGURE 1 is a schematic of a prior art fuel cell control system a power conversion stage between the fuel cell and the energy storage device;

[0011] FIGURE 2 is a schematic of the fuel cell control system of the present invention;

[0012] FIGURE 3 is a graph of the voltage-current characteristics of an energy storage device;

[0013] FIGURE 4 is a graph of the voltage-current characteristic of a fuel cell using the control system of the present invention;

[0014] FIGURE 5 is a flow chart of the method of the present invention; and

[0015] FIGURE 6 is a graph of the voltage-current characteristics of the fuel cell and energy storage device overlaid to illustrate the control method of the present invention.

Detailed Description Of Preferred Embodiments

[0016] Figure 1 shows a prior art fuel cell control system 10 a dc/dc power conversion stage 12. The purpose of the power conversion stage 12 is to interface the fuel cell 14 with an energy storage device 16, such as a battery (shown) or an ultracapacitor (not shown) and a load 18. It is also possible to use the power conversion stage 12 to interface the fuel cell 14 directly to the load 18.

[0017] The present invention provides a system and method for controlling a fuel cell, the outputs of an energy storage device, and the state-of-charge (SOC) of the energy storage device to supply a demanded load.

[0018] Figure 2 is a block diagram of the fuel cell control system 20 of the present invention. A controller 22 controls predetermined variables 21 to adjust a voltage of a fuel cell 24. The variables include, but are not limited to, the mass flow rate of air (Ma) and fuel (Mf), the pressure of the air (Pa) and fuel (Pf), the temperature (Tc) of the fuel cell 24, the humidity of the air and hydrogen, and the current (Ifc) drawn in the fuel cell 24. The predetermined variables are manipulated in response to total power of a load 26 on the combination of the fuel cell 24 and an energy storage device 28, such as a battery as shown in Figure 2.

[0019] An optional dc/dc converter (not shown in Figure 2) may be used to take a dc voltage from the energy storage device 28 and convert it to a dc voltage that is required to run an inverter (not shown) or directly couple to the load 26. The dc/dc converter

may convert the dc voltage to a higher or a lower voltage. According to the present invention, the converter is optional. The prior art example shown in Figure 1 requires a power converter between the fuel cell and energy storage device.

[0020] In the present invention, and referring to Figure 2, the fuel cell 24 is controlled to act as a charger for the energy storage device 28, shown as a battery in Figure 2, but could also be an ultracapacitor or other device. The fuel cell 24 is directly paralleled to the energy storage device 28. According to the present invention, there is no need for the intermediate power conversion stage as in the prior art example shown in Figure 1.

[0021] Referring again to Figure 2, a diode 30 may be used to block current from flowing from the energy storage device 28 into the fuel cell 24. Such reverse current may cause damage to some types of fuel cells. The diode 30 is optional and may be absent.

[0022] The fuel cell 24 has a voltage (V_{cell}) that is controlled according to the present invention so that it is compatible with a voltage (V_{bat}) at the energy storage device 28. The fuel cell voltage (V_{cell}) and the energy storage device voltage (V_{bat}) are made compatible as a function of load current (I_{load}) and the SOC of the energy storage device 28. The load current I_{load} is measured by the controller 22 at the load 26 and is used to determine a demand current for the fuel cell 24.

[0023] The fuel cell voltage V_{cell} is a non-linear function having several controllable parameters. These include, but are not limited to;

M_f = the mass flow rate of fuel

M_a = the mass flow rate of air

P_f = the pressure of the fuel

P_a = the pressure of the air

RH_a = the humidity of the air

T_c = the temperature of the fuel cell

I_{fc} = the current drawn in the fuel cell

[0024] The voltage of the energy storage device, V_{bat} is also a function of several parameters, including but not limited to;

SOC = state of charge of the energy storage device

I_b = the current into or out of the energy storage device

T_b = the temperature of the energy storage device

A_b = the age of the energy storage device

[0025] Through modeling, measurement and control of a subset of all of the controllable parameters in the fuel cell voltage and the parameters in the energy storage device, the voltage-current characteristics of both of these devices are coordinated to achieve control of the SOC of the energy storage device. By controlling the SOC, the life of the energy storage device is extended and an adequate reserve energy margin is maintained. The reserve energy makes it possible to handle temporary high-load current conditions that are due to fluctuations in the external load 26.

[0026] The cell voltage is given by:

$$V_{cell} = V_{Th} - (RT/2F)\ln(PH_2O/PH_2)*(1/(PO_2)^{1/2} \quad (1)$$

where V_{cell} is the cell voltage and V_{Th} is the theoretical Nernst voltage. The Nernst voltage is a theoretically calculated voltage that represents the maximum cell voltage that can be obtained, assuming there are no losses. (PH_2O/PH_2) is the partial pressure of water and Hydrogen gas in the fuel, PO_2 is the partial pressure of Oxygen gas in the oxidant, R is the gas constant and T is the cell temperature.

[0027] An average cell voltage can be calculated by monitoring the cell conditions and applying equation (2) as follows:

$$V_{cell}=[(1-\alpha)V_{in}+\alpha V_{out}-IR_{eff}+RT/2F\ln(1-(I_{cell})/I_{limit}))] \quad (2)$$

[0028] where V_{in}, and V_{out} are the Nernst voltages for inlet and outlet conditions, α is the weighting factor for the cell voltage, R_{eff} is the effective cell resistance at temperature, T, I_{cell} is the cell current and I_{limit} is the limiting current. The limiting current is dependent upon the cell behavior and each cell will have its own limiting current depending on the system.

[0029] The effective cell resistance, R_{eff} is given by:

$$R_{eff}=R_o e^{[(\sigma t*To)/Ro][\ln(To/Tcell)]} \quad (3)$$

where R_o is the effective cell resistance at a reference temperature T_o, σ_t is the temperature coefficient, and T_{cell} is the average cell temperature.

[0030] Figure 3 is a graph of a voltage-current characteristic 300 for the energy storage device and Figure 4 is a graph of a voltage-current characteristic 400 for the fuel cell. The voltage-current characteristic 300 of the energy storage device is a

non-linear function of the current. The characteristic 302 represents the battery having a low SOC and the characteristic 304 represents the battery having a high SOC.

[0031] Referring now to Figure 4, the fuel cell characteristic 400 is shown as a fuel cell curve 402 for a low SOC and a fuel cell curve 404 for a high SOC. The controller manipulates the fuel cell curves 402, 404 as the load current (I_{load}) varies, thereby controlling the SOC of the energy storage device. The operating point for a given load current occurs at the intersection of the curves and is shown later herein with reference to Figure 6 following the description of the method of the present invention.

[0032] The method 100 of the present invention is described in conjunction with Figure 5. The present invention determines 102 the desired change in the energy storage device's state of charge. This is accomplished by way of a comparison of a current SOC with the SOC target, shown in Figure 2 at 32. The load current I_{load} is measured 104 by way of the controller.

[0033] The method then determines 106 the desired amount of load current that is provided by the fuel cell so that the SOC of the energy storage device is increased or decreased as desired. Through dynamic system modeling of the fuel cell voltage equations, as described above, predetermined parameters are manipulated 108 according to the measured value of the load current I_{load}. The fuel cell voltage V_{cell} is controlled 106 as a function of the load current I_{load}. Thereafter, the energy storage device SOC is controlled 108 as a function of the fuel cell voltage V_{cell}.

[0034] Figure 6 illustrates an example 600 of the operation of the system and method of the present invention. Figure 6 is a graph of the voltage-current characteristics 602, 604 for the energy storage device with respect to axis 606. The fuel cell voltage-current characteristics 608, 610 are shown with respect to axis 612. The axis 606 and the axis 612 are offset with respect to each other by the load current 614. As the load current varies, the distance between the two axes 606 and 612 will vary in direct proportion.

[0035] At a given load current, the SOC of the energy storage device is controlled as follows. Assume the starting SOC for the energy storage device is represented by the voltage-current characteristic 602, which shows the characteristic of the energy storage device 20% SOC. When the fuel cell is controlled such that its voltage-current characteristic is described by the curve 608, the intersection of the curves 602 and 608 will determine an operating point 616. The load current will be apportioned into an energy storage device current 618 and a fuel cell current 620.

[0036] For instances where the SOC is to be increased for the given level of load current, the predetermined control parameters of the fuel cell are adjusted, according to the fuel cell voltage equations described herein as well as any linear or non-linear system models that may be necessary. The fuel cell voltage current characteristic curve becomes as shown at 610.

[0037] Immediately after the control is adjusted as described above, the energy storage device characteristic 602 and the fuel cell characteristic 610 intersect to reach a new operating point that is now shown at 622. At the operating point 622, the energy storage device is being charged and the load current is still being served. As the energy storage device SOC increases to 100%, the voltage-current characteristic will change until the time where 100% SOC is reached. At this point, the energy storage device voltage-current characteristic 604 applies, and a final operating point of 624 is defined. At the final operating point 624, the energy storage device has zero current and the load current is supplied entirely by the fuel cell.

[0038] By modifying the predetermined control parameters, control over a full range of the state of charge can be achieved. A desired division of load current between the fuel cell and the energy storage device can also be achieved.

[0039] The invention covers all alternatives, modifications, and equivalents as may be included within the spirit and scope of the appended claims.